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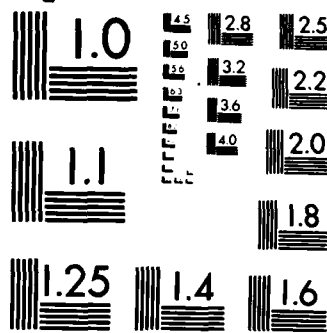
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MILLIMETER WAVE MOISTURE SOUNDER FEASIBILITY STUDY:
THE EFFECT OF CLOUD AND PRECIPITATION ON
MOISTURE RETRIEVALS

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8 August 1984 - 7 February 1985

8 March 1985

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"This technical report has been reviewed and is approved for publication"


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FOR THE COMMANDER


for ROBERT A. McCLATCHEY, Director
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<p>A simulation model applicable to the design specification of a millimeter wave moisture sounder is described. The algorithm is capable of treating the response of a multifrequency radiometer to realistic variations in vertical profiles of atmospheric temperature and moisture, surface emissivity, cloud and precipitation. Analyses were performed to investigate the sensitivity of proposed moisture sounder channels to changes in the vertical distribution</p>		

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of atmospheric water vapor and the presence of cloud and rain. Preliminary studies based on statistical inversion methods demonstrate moisture retrieval capabilities in clear, cloudy, and precipitating cases. Results indicate that cloud and precipitation will most likely degrade moisture sounder performance. Investigation of moisture retrieval methodologies which explicitly treat cloud effects is recommended.

Keywords: Atmosphere, precipitation, Satellite
remote sensing, Computer codes, Multiple
scattering, Radiative transfer, Clouds

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1. Technical Objectives

This report summarizes the results of a Phase I Small Business Innovation Research (SBIR) Program effort recently completed at Atmospheric and Environmental Research, Inc. (AER) to develop simulation models applicable to the design specification of a millimeter wave (MMW) moisture sounder operating at 183 GHz. The goal of the initial study was to develop computer algorithms capable of treating the response of a multifrequency radiometer to realistic variations in relevant meteorological variables potentially affecting its operational performance. These variables include vertical profiles of temperature and moisture, surface emissivity variations, and the presence of cloud and precipitation. Although the design specification process for a profiling radiometer typically includes three stages, i.e. instrument response simulation, sensitivity analyses, and retrieval performance assessment, the focus of the Phase I effort was placed on the simulation stage since its successful implementation is critical to providing meaningful results for subsequent analyses. As proposed in the Phase I work plan, the specific technical objectives of the effort were:

- (1) development of instrument response simulation models capable of treating a representative range of variables potentially encountered in the atmosphere, including realistic cloudy and precipitating cases;
- (2) testing and validation of the simulation models; and
- (3) performing a limited number of sensitivity analyses in order to provide initial guidance for later stages of design specification.

A fundamental question which was identified to be answered during Phase I with respect to item (3) concerned the potential adverse impact of cloud liquid water and hydrometeors on the retrieval of water vapor profiles. As posed during Phase I, the effect of cloud and precipitation was of concern in assessing the potential "all-weather" capabilities of MMW moisture profile radiometers.

2. Background

The significance of improved capabilities to specify the global moisture field (including water vapor, cloud, and precipitation) potentially afforded

by an optimally designed millimeter wave moisture sounder cannot be underestimated. Implications for numerical weather prediction (NWP) are particularly promising (Kaplan et al, 1983). Radiatively, water in its many forms is the most active constituent of the troposphere. Clouds and water vapor, for example, profoundly affect the infrared temperature retrieval problem (Chahine, 1974, 1982) and the parameterization of radiative heating (WMO, 1978). A variety of studies have shown that updating the moisture field can improve short range precipitation forecasts (Perkey, 1980; Maddox et al., 1981) and that latent heat release associated with condensation can have large short term influence on storm development (Anthes et al., 1983). Knowledge of the moisture field is also of great importance for meeting the Air Force's operational requirements for better cloud forecasts (Mitchell and Warburton, 1983).

Current operational moisture sounder channels including the HIRS-2 of the TIROS-N Operational Vertical Sounder (TOVS) (Smith et al., 1979) and the Defense Military Satellite Program (DMSP) SSH/2 (Barnes Engineering, 1978), are exclusively infrared, exploiting the rotation-vibration bands near $6.7 \mu\text{m}$ (in three channels) and the pure rotation bands near $20 \mu\text{m}$ (in seven channels), respectively. In general, there has been a lack of success in obtaining operationally useful water vapor profiles using statistically-based retrieval approaches. Goals for TOVS moisture retrievals, for example, are limited to precipitable water values in three broad vertical layers at accuracies of $\pm 30\%$ (NOAA, 1981). Recently, investigators using combined physical-statistical methods (cf. Reuter and Susskind, 1983; Kaplan and Isaacs, 1984) have fared somewhat better, demonstrating improvement over climatological first guess profiles. Problems associated with infrared water vapor profile retrievals include (Conrath, 1969; Chahine, 1972; Smith and Woolf, 1976; Zeng, 1979; Hayden et al., 1981; Rosenberg et al., 1983): (a) cloud contamination; (b) sensitivity of retrieved humidity structure in the lower atmosphere to the effects of surface emission; (c) errors due to the non-linear dependence of the humidity retrieval to errors in the temperature retrieval, and (d) the inability to resolve vertical moisture structure due to broadness of weighting functions. In order to circumvent some of these apparent difficulties, especially those associated with cloud contamination and the effect of unit emissivity on retrieval of moisture in near surface layers, a trend has recently emerged toward microwave moisture sounding.

Microwave water vapor remote sensing in the past has used the weak rotational line at 22.235 GHz (total zenith attenuation of 0.5 dB for 1.5 cm precipitable water, Smith and Waters, 1981) which cannot provide sufficient opacity for reliable vertical profiling. For this reason, research has focused on column integrated (i.e., total precipitable) water vapor over the ocean (Staelin et al., 1976; Grody and Pellegrino, 1977; Liou and Duff, 1979; Chang and Wilheit, 1979; Grody et al., 1980; Prabhakara et al., 1982; Alishouse, 1983). A stronger feature (by about two orders of magnitude) available for vertical moisture profiling in the millimeter wave (MMW) region is the ($3_{13} - 2_{20}$) water vapor rotational transition located at 183.31 GHz (Schaerer and Wilheit, 1979). An aircraft instrument utilizing this concept called the Advanced Microwave Moisture Sounder (AMMS) has been flown and successful retrievals performed under essentially clear sky conditions (Wang et al., 1983). A comparable set of channels has been proposed to provide moisture profiling capabilities (at 15 km resolution) within the next generation Advanced Microwave Sounding Unit (AMSU) envisioned as a 1990s implementation concurrent with the first NOAA-NEXT series launch (Schultz, 1982; NOAA, 1983). This system (called the AMSU-B) is currently under study at the Jet Propulsion Laboratories (JPL) in the US and the Rutherford Appleton Laboratory (RAL) in the UK (D. Pick, personal communication). A similar enhancement designated the SSM/T-2 (although at 50 km resolution) has been suggested to supplement the DMSP microwave temperature sounder (SSM/T).

Satellite-borne microwave instruments have generally offered advantages over their infrared counterparts, particularly with respect to cloud and surface emissivity effects. At the longer wavelengths (two to three orders of magnitude) associated with microwaves, most non-precipitating liquid water clouds are quite optically thin and ice clouds are virtually transparent. Even at half centimeter wavelengths (i.e. ~ 60 GHz), for example, clouds appear to have little effect on temperature profile retrievals (Staelin et al., 1975; Liou et al., 1981; Grody et al., 1984), although window brightness temperatures are affected by cloud and rain (cf. Toong and Staelin, 1970). This advantage is seriously degraded, however, at shorter millimeter waves. Earlier simulation studies noted the potential adverse effect of cloud on MMW temperature retrievals (Gaut et al., 1975; Staelin et al., 1978). Although the effect of cloud cover on moisture retrieval had been alluded to previously (cf. Schaerer and Wilheit, 1979), and one early study suggested using 140,

170, and 183 GHz channels to discriminate between clear, liquid water, and glaciated clouds (Gaut et al., 1975), current MMW studies have focused primarily on the development of clear sky moisture retrieval algorithms (Rosenkranz et al., 1982; Wang et al., 1983; Kakar, 1983; Kakar and Lambrigtsen, 1984). Synoptic cloud reports indicate, however, that over the data sparse open ocean, skies are completely clear only about 2-5 percent of the time (Hahn et al, 1982). This raises an important question concerning the effect of cloud on MMW moisture retrieval capabilities. Notably, the millimeter wavelength optical properties of clouds have been increasingly of interest to workers in active remote sensing (Lhermitte, 1981a,b; Pasquallucci et al., 1983; Hobbs and Funk, 1984) and calculations of millimeter wave attenuation by clouds have been available for some time (Deirmendjian, 1975).

Additionally, while the effects of precipitation on microwave atmospheric remote sensing have been treated previously (Isaacs, 1974; Gaut et al., 1975; Savage and Weinman, 1975; Savage, 1978) recent attention has focused on MMW scattering by rain and particularly by precipitation-sized ice particles (Wilheit et al, 1982; Huang and Liou, 1983; Szejwach et al., 1983; Yeh et al, 1983; Wu and Weinman, 1984). This suggests the necessity for an MMW multiple scattering calculation of radiative transfer in order to appropriately model the effect of precipitation on proposed MMW moisture sounders.

3. Simulation Model Development

The technical approach adopted to simulate MMW radiometer response is illustrated in Figure 1. System response is evaluated for the desired multi-channel experimental configuration and viewing geometry using an interaction model based on radiative transfer theory. The requisite vertical profiles of optical properties to facilitate this calculation are based on physical models supported by relevant meteorological data. Interaction mechanisms determining the transfer of radiation through the atmosphere include absorption by gases and absorption and scattering by clouds and precipitation (both liquid and glaciated). Since satellite borne sensors view against the earth's surface, its emissive (and reflective) properties are also of interest. Physical models thus include three important groups of submodel: (a) gaseous absorption, (b) cloud attenuation and precipitation extinction, and (c) surface emission properties.

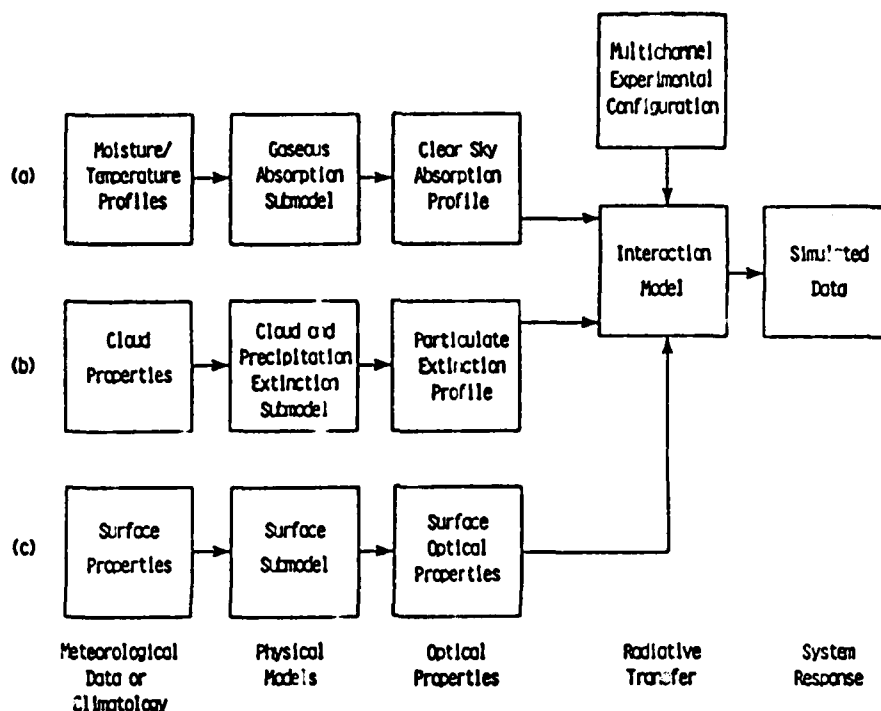


Figure 1. Simulation Algorithm Flowchart

At the frequencies of interest here, clear sky absorption is due primarily to water vapor and to a lesser extent oxygen (Waters, 1976). Ozone also absorbs in this spectral region, but has negligible effect on brightness temperature simulations. The models adopted for gaseous absorption are taken from AFGL's RADTRAN (Falcone, personal communication) code with water vapor absorption evaluated using the expression of Barrett and Chung (1962) for frequencies less than 60 GHz, the 183 GHz line plus the non-resonant background (see Gaut and Reifenstein, 1971) between 60 and 300 GHz, and summing over a set of 54 rotational lines (including that at 183.31) using the constants of Gaut and Reifenstein (1971) and the VanVleck-Weisskopf (1945) line shape at higher frequencies. The water vapor continuum (see Waters, 1976) is based on the empirical fit of Gaut and Reifenstein (1971) which provides an adequate model at moderate relative humidities (see Liebe and Layton, 1983) but has questionable temperature dependence (Burch, 1981). Oxygen absorption is evaluated using the parameters of Meeks and Lilley (1963). (The correction for first order coherence effects in overlapping lines (Rosenkranz, 1975) has not been implemented in the current version but is of little consequence for calculations at 183 GHz.) Many of these expressions are summarized

in Falcone et al. (1971). An error in the coding logic of the original RADTRAN brightness temperature calculation was noted and corrected in the final version adopted for our simulations.

The cloud models chosen are those from AFGL's AERSOL subroutines provided in FASCODE (Falcone et al., 1979) largely based on those of Silverman and Sprague (1970). Cloud attenuation is evaluated using the mass density of the selected cloud model and index of refraction data from Ray (1972). Data for ice are obtained from Warren (1983). When precipitation (liquid or solid) is present a multiple scattering calculation is generally required necessitating particulate scattering optical properties such as extinction coefficient, single scattering albedo and angular scattering functions, to be provided through a physical submodel based on Mie theory calculations (Dave, 1972). Although precipitation size distribution models vary (Crane, 1966; Fowler et al., 1976) that of Marshall and Palmer (1948) is ubiquitous and has been adopted for this calculation. To eliminate the necessity to perform Mie theory calculations concurrent with each rain rate and frequency dependent simulation, all scattering properties required by the multiple scattering code are provided by a subroutine developed specifically for this purpose based on a parameterization by Savage (1978). This subroutine provides an efficient method to obtain extinction coefficient, single scatter albedo, and the first eight Legendre polynomial expansion coefficients of the angular scattering function using interpolation methods in the domain from about 19 to 240 GHz. Figure 2 compares exact Mie theory calculations and those obtained from the subroutine parameterization developed to provide the desired scattering quantities. The values returned from the parameterization are quite accurate and adequate for subsequent evaluation of brightness temperatures. Brightness temperatures calculated using the two methods differed by at most 0.2 K and were generally negligibly different.

The interaction model uses both atmospheric and surface optical properties to simulate multichannel radiometer data for a given observational configuration. Surface optical properties are required in the form of frequency dependent surface emissivities, ϵ_i . These values are obtained from physical submodels specific for ocean and land surfaces. Over the ocean, surface emissivity is related to wind speed dependent surface roughness (cf. Wilheit,

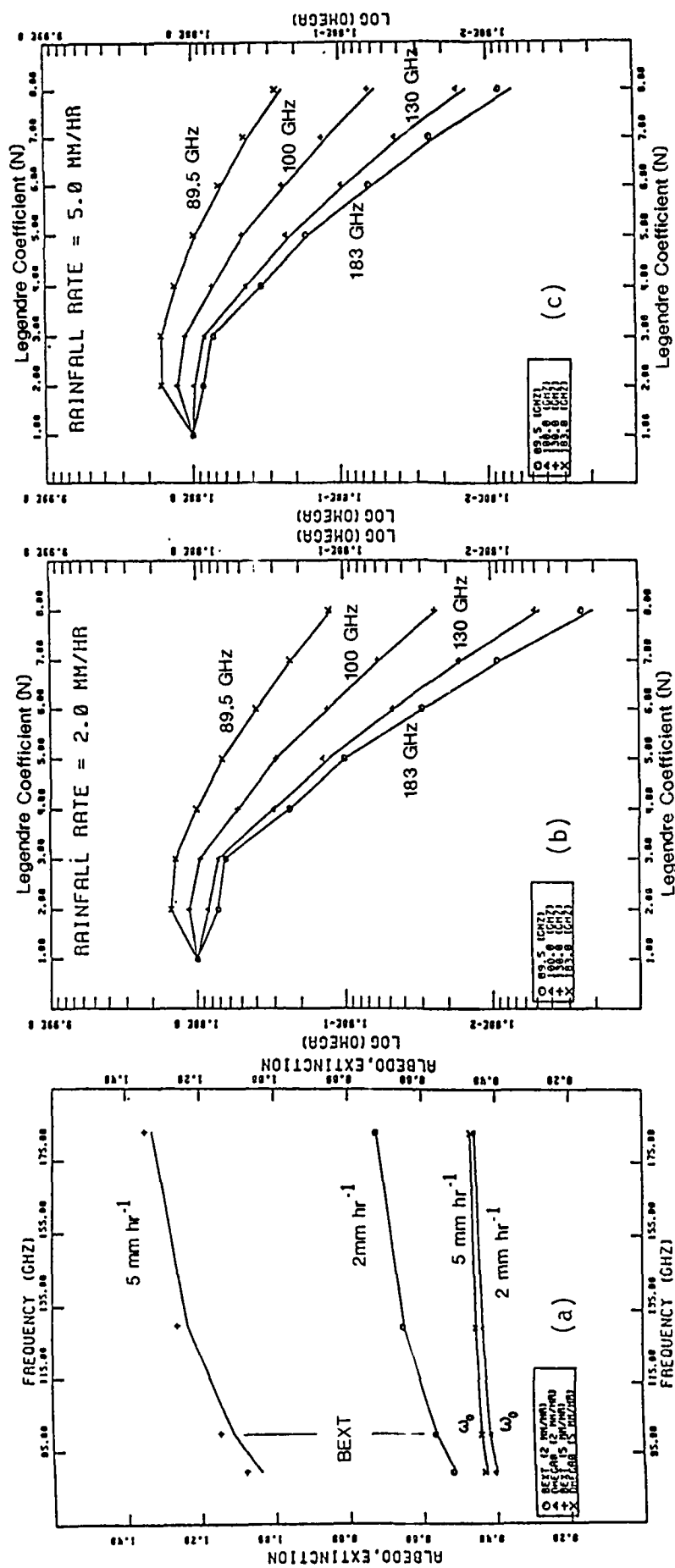


Figure 2. Comparison of exact (symbols) and parameterized (lines) scattering parameters of rain: (a) extinction coefficient and single scatter albedo (2, 5 mm/hr), (b) first eight Legendre coefficients (2 mm/hr), (c) same (5 mm/hr).

1979; Wentz, 1983). Our model is based on that of Stogryn (1967) as described in Gaut and Reifstein (1971) and Fowler et al. (1977). Over land, emissivities are spatially variable at the frequencies of interest and models are generally based on statistical approaches supported by a few measurements (e.g. Hardy et al., 1981). Instrumental noise is simulated by adding a Gaussian noise term of specified standard deviation (~1-2 K). Radiative transfer (RT) techniques are applied in the interaction model with simulated brightness temperatures, for look angle θ and channel i given by:

$$\vec{T}_i(\theta) = \vec{T}_i(p_s) \tau_i(\theta, p_s) + \int_{p_s}^0 \vec{S}(p) \frac{d}{dp} \tau_i(\theta, p) dp \quad (1)$$

where $\vec{T}_i(p_s)$ and $\vec{S}(p)$ are, respectively, the effective surface brightness temperature and the atmospheric source function given by:

$$\vec{T}_i(p_s) = \epsilon_i T_s + (1 - \epsilon_i) T^\downarrow(p_s) \quad (2)$$

$$\vec{S}(p) = [1 - \omega_i(p)] T(p) + \omega_i(p) \vec{J}_i(p, \Omega) \quad (3)$$

where the scattering source function is given by:

$$\vec{J}_i(p, \Omega) = \int \tilde{P}_i(p, \Omega, \Omega') \vec{T}_i(p, \Omega') \frac{d\Omega'}{4\pi} \quad (4)$$

Here, T_s is the physical surface temperature, $T^\downarrow(p_s)$ is the downwelling brightness temperature field, and $\vec{T}(p, \Omega)$ is the scattered brightness temperature field within the atmosphere. Vector quantities above correspond to horizontal and vertical polarization components, i.e. $\vec{X} = (X_h, X_p)$ and \tilde{P} is the matrix based on single scattering theory whose cross elements determine polarization mixing due to atmospheric scattering. The solution reduces to the familiar brightness temperature simulation relation when there is no precipitation scattering (i.e., $\omega_i(p) = 0$). In the presence of large hydrometeors, however, a multiple scattering (MS) solution is required.

In the adopted simulation code, the MS calculation is accomplished using the discrete ordinate method (DOM) (Liou, 1973). In this approach the scalar radiative transfer equation for brightness temperature within the scattering cloud is reduced by Gaussian quadrature of degree n to a set of $2n$ coupled differential equations:

$$\mu_i \frac{dT_i(\tau)}{d\tau} = T_i(\tau) - \sum_{j=1}^n (C_{i,-j} T_{-j} + C_{i,j} T_j) - (1-\omega)T \quad (5)$$

where T_i is the brightness temperature at the i th Gauss zenith angle cosine μ_i and

$$C_{i,j} = \frac{1}{2} \omega_0 \sum_{\ell=0}^{2n-1} a_j (2\ell+1) \omega_\ell P_\ell(\mu_i) P_\ell(\mu_j). \quad (6)$$

In the above expression the ω_ℓ 's are coefficients of the Legendre polynomial expansion of the phase function and the a_j are the Gaussian quadrature weights ($a_j = a_{-j}$; $\mu_{-j} = -\mu_j$). The solution for each T_i is given by:

$$T_i = \sum_{j=-n}^n L_j g_j(\mu_j) \exp(-k_j \tau) + T_c \quad (7)$$

where the g_j and k_j are the eigenvectors and eigenvalues, respectively, T_c is the cloud temperature and the L_j 's are constants determined by the boundary conditions. The version of the DOM code chosen for implementation (Liou et al., 1980a) had never been run at AFGL due to machine conversion difficulties, required input of the ancillary MMW scattering data described above, did not treat arbitrary sensor zenith angles, and did not treat polarization (i.e., the vectorized radiative transfer equation above). To address these issues, Phase I accomplishments included:

- Converting and successfully debugging the discrete ordinate method (DOM) multiple scattering code on the AER Harris H800, running test case intercomparisons, and reconvertng the working code for use on the AFGL CDC Cyber system.
- Evaluating the cloud and precipitation optical properties required for use in the DOM code including single scattering albedo and angular scattering functions at 90, 100, 130, 150, 166, and 183 GHz.
- Developing a parameterization subroutine for evaluating these scattering properties eliminating the need for on-line Mie theory calculations with the DOM and concurrently providing simple meteorological parameters (i.e. rain rate, phase, etc.) as input data.

- Converting the DOM algorithm for arbitrary sensor zenith angles and pseudo-polarized capability (i.e. cross polarization scattering elements are neglected to first order and polarization enters only through the surface emissivity variation). This provides the capability to simulate other than nadir viewing angles when large droplets do not influence scattering in the field of view.

Figures 3 and 4 illustrate typical calculations simulating the effect of precipitation on remotely sensed microwave/millimeter wave brightness temperatures performed using the simulation code described above. Illustrated are brightness temperature/rainfall rate relationships for nadir viewing over ocean (Fig. 3) and land (Fig. 4) evaluated at microwave imager (19.35, 37, 90.0 GHz) and millimeter wave sounder (150, 166, 183±7, ±9 GHz) relevant frequencies. The former set of channels are primarily for imaging while the latter set are for sounding. These results predict a variety of characteristic features discussed by investigators which have been previously used in the design of existing microwave sensors. For example, the difference in 19.35 and 37.00 GHz response to increasing rainfall rate over land and ocean is evident (cf. Savage and Weinman, 1975). While the 37 GHz brightness temperatures over the ocean saturate at relatively low rain rates compared to those at 19.35 GHz, the situation is reversed over land, with little sensitivity, if any, to increases in rain at 19.35. Figure 4 suggests that 90 GHz may be even more sensitive to low rainfall rates (i.e. $< 10 \text{ mm hr}^{-1}$) over low land. Delivery of this simulation code concurrent with submission of this report provides a previously unavailable simulation modeling capability to AFGL users.

4. Model Application

The simulation model described in the previous section was applied both: (a) to investigate the sensitivity of calculated nadir channel weighting functions and brightness temperatures to realistic variations in atmospheric, surface, and instrumental characteristics, and (b) to ascertain the potential utility of these simulated data (i.e. the brightness temperatures) to infer water vapor vertical profiles. Nine channel frequencies were chosen for simulation corresponding to those collectively designated for use in three individual existing or proposed instruments: the Advanced Microwave Moisture Sounder (AMMS) (Wang et al., 1983), the DMSP Microwave Moisture Sounder Enhancement (SSM/T-2) (see Isaacs and Kaplan, 1983), and the Advanced Microwave

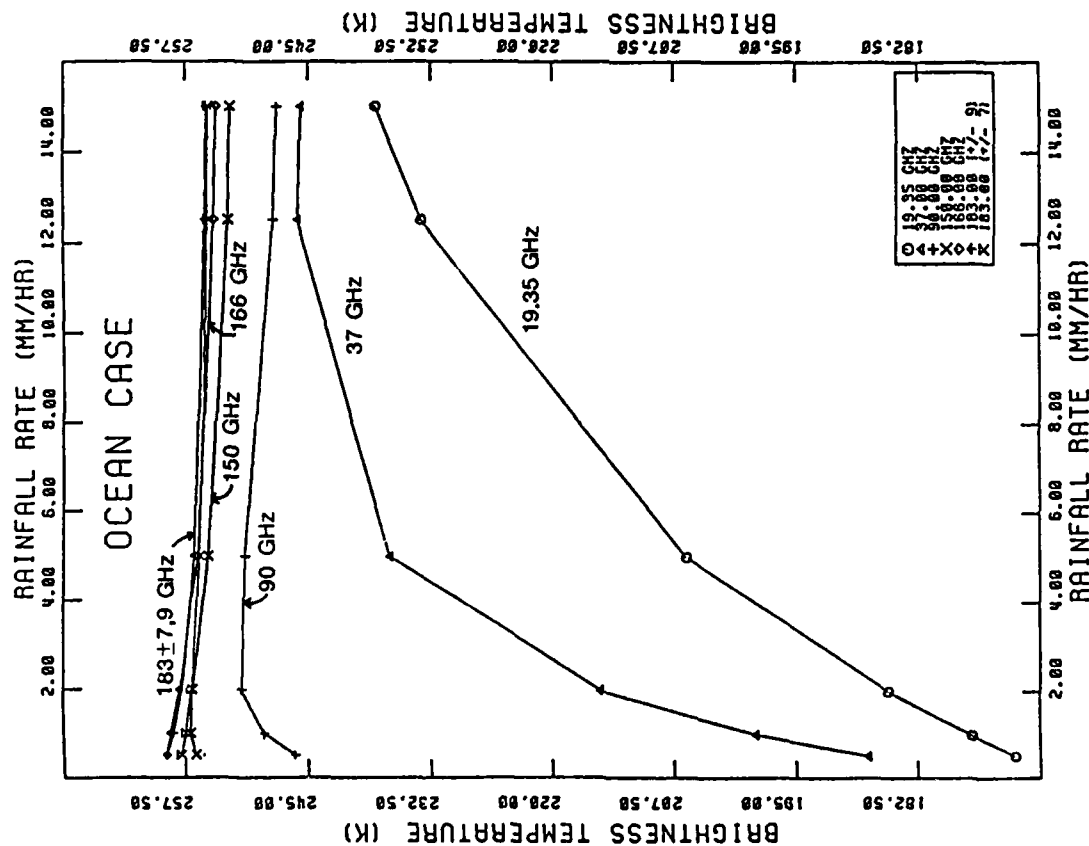


Figure 3. Nadir brightness temperature vs. rainfall rate over ocean at 19.35, 37.0, 90.0, 150.0, 166.0, and 183.0±9, ±7 GHz.

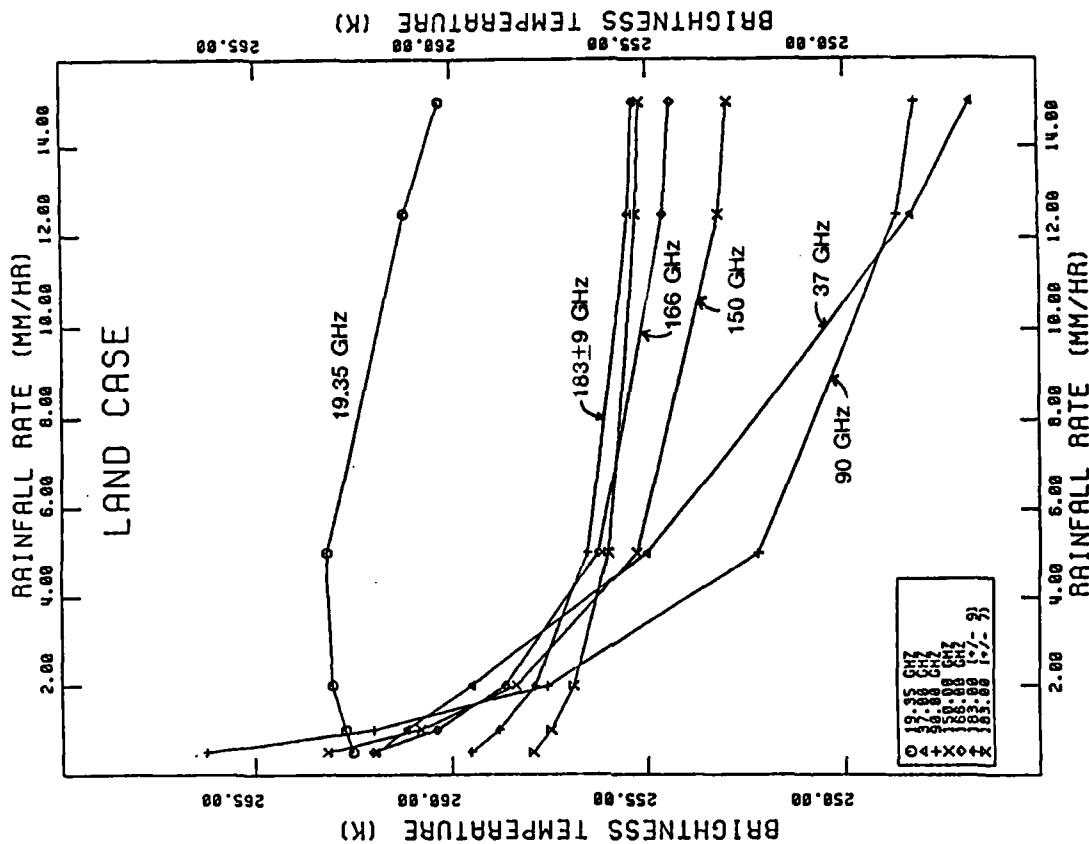


Figure 4. Nadir brightness temperature vs. rainfall rate over land at 19.35, 37.0, 90.0, 150.0, 166.0, and 183.0±9, ±7 GHz.

Sounder (AMMS) (Wang et al., 1983), the DMSP Microwave Moisture Sounder Enhancement (SSM/T-2) (see Isaacs and Kaplan, 1983), and the Advanced Microwave Sounding Unit water vapor package (AMSU-B) envisioned as a 1990s implementation concurrent with the first NOAA-NEXT series launch (Schultz, 1982; NOAA, 1983). For completeness, a channel centered at the water vapor line center, 183.31 GHz was also included. A fourth "instrument" which hypothetically has all ten of the above channels available (designated MMW) was also examined. These frequencies are shown in Table 2. (Note that subsequent to completion of our studies, an 89.5 GHz channel was also proposed for SSM/T-2, Falcone, personal communication.) The atmospheric profiles used in these simulations were restricted to tropical atmospheres from among the set of 1600 clear and cloudy radiosondes prepared for use in the NOAA-NESS/NASA System 85 Test (Halem, 1984) which compared the capabilities of the operational HIRS-2 and the proposed AMTS infrared temperature sounders. The representativeness of the sensitivity and retrieval performance tests must be considered limited by the climatologically restricted nature of the sample set used.

Table 2
Millimeter Wave Sounders

Channels	Freq.	AMMS	SSM/T-2	AMSUB	Noise (K)	
					1	2
7	183.31					
6	183.31±1		x	x	1.0	2.0
5	183.31±2	x			1.2	2.0
4	183.31±3		x	x	1.5	2.0
3	183.31±5	x			1.6	2.0
2	183.31±7		x	x	1.8	2.0
1	183.31±9	x			2.0	2.0
8	90	x		x	1.0	2.0
9	150		x		1.0	2.0
10	166			x	1.0	2.0

4.1 Sensitivity Studies of Channel Brightness Temperatures

The sensitivity of simulated weighting functions and brightness temperatures at the frequencies designated above was calculated for representative

changes in layer water vapor abundance, cloud presence, rain presence, and water vapor variation over low cloud. The above sensitivity tests were performed over both ocean and land surfaces. Figure 5, for example, shows the modifying effect of an altostratus cloud located between 2.5 and 3.0 km on six of the selected channels evaluated for one of the tropical radiosonde profiles (the other four frequencies are closer to the line center and thus have weighting functions peaking above the cloud). The shift in the weighting function to the vicinity of the cloud top is quite evident suggesting a pronounced effect on the brightness temperatures. As might be expected, the impact of rain is even more drastic.

In order to retrieve information on the vertical distribution of water vapor, channel brightness temperatures must show sensitivity to its variation. Figure 6 illustrates such a sensitivity assessment under clear conditions over both ocean and land backgrounds. Plotted at each of six pressure levels (corresponding to the layer midpoints of layers bounded by: 0-200, 200-300, 300-500, 500-700, 700-850 mb, and 850-1000 mb, respectively) is the change in brightness temperature (ΔT_B) due to an increase in layer integrated water vapor abundance, q , by 20% where $\Delta T_B = T_B(q) - T_B(1.2q)$. Values near zero indicate little sensitivity to layer water vapor variations, i.e. such values indicate that a particular channel will not sense a change in water vapor at the indicated pressure. Notably, this lack of sensitivity characterizes most of the sounding channels (i.e. 183 \pm , etc.) near the surface. Over the ocean, however, relatively strong negative signals are available from "window" channels (i.e., 90, 150, 166 GHz) as water vapor appears in emission over the relatively low emissivity ocean surface.

To investigate the sensitivity of brightness temperatures to the presence of cloud, simulations were performed for a set of ten radiosonde profiles (five over ocean, five over land) at the frequencies listed in Table 2 for both clear and cloudy conditions. The cloud modeled in each case was an altostratus layer located between 2.5 and 3.0 km. The assumed cloud microphysics is that of Silverman and Sprague (1970) as given by Falcone et al. (1979) with liquid water content of about 0.4 gm⁻³. In all cases, the cloud was assumed to fill the field of view. Figure 7 illustrates the brightness temperature difference ΔT_B between the simulated clear brightness temperature, $T_B(\text{clr})$, and that calculated with cloud present $T_B(\text{cld})$ for each frequency

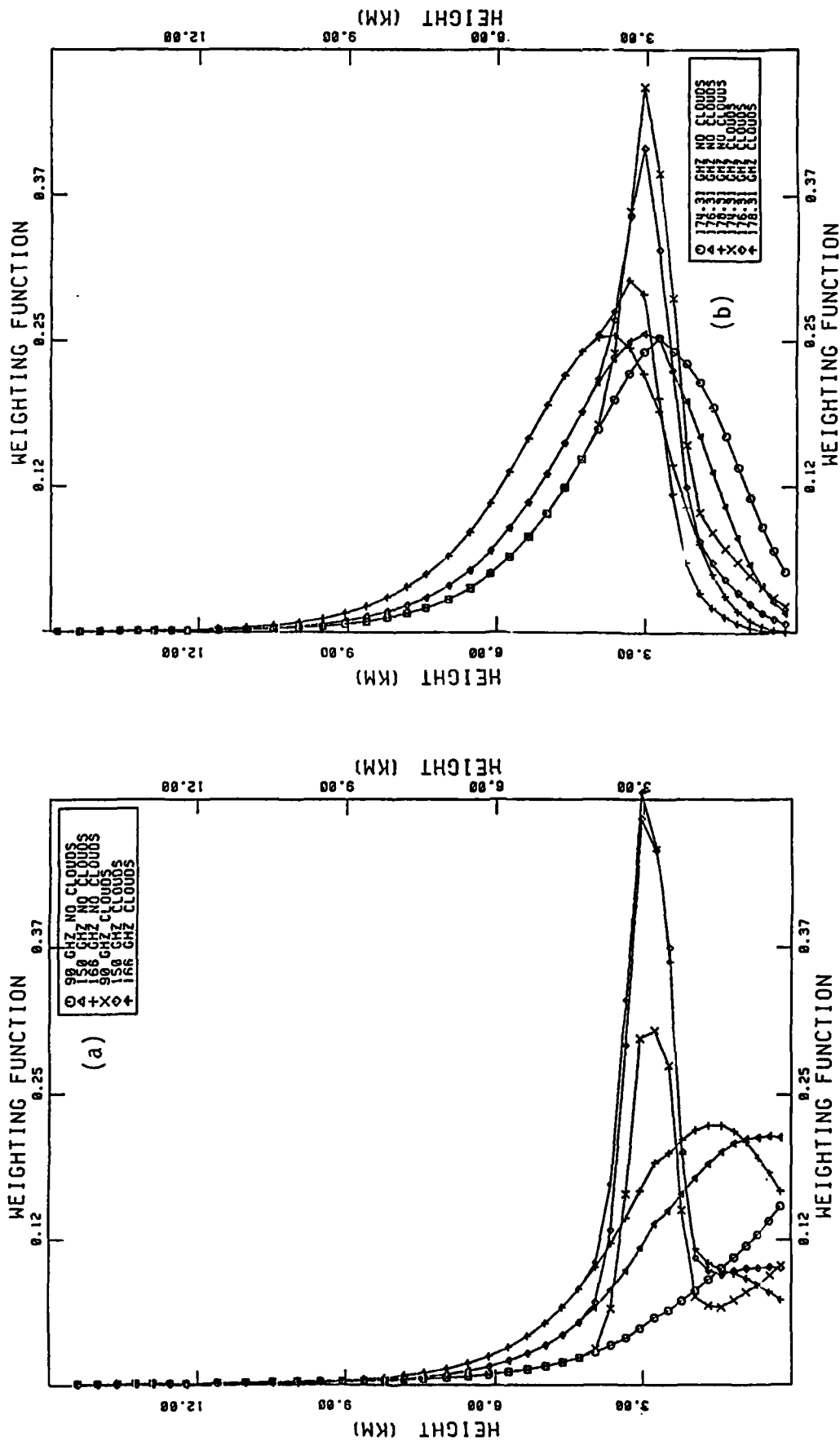


Figure 5. Modifying effect of altostratus cloud (2.5-3.0 km) on millimeter wave weighting functions over the ocean: (a) 90, 150, 166 GHz, (b) 183.31 \pm 5, \pm 7, \pm 9.

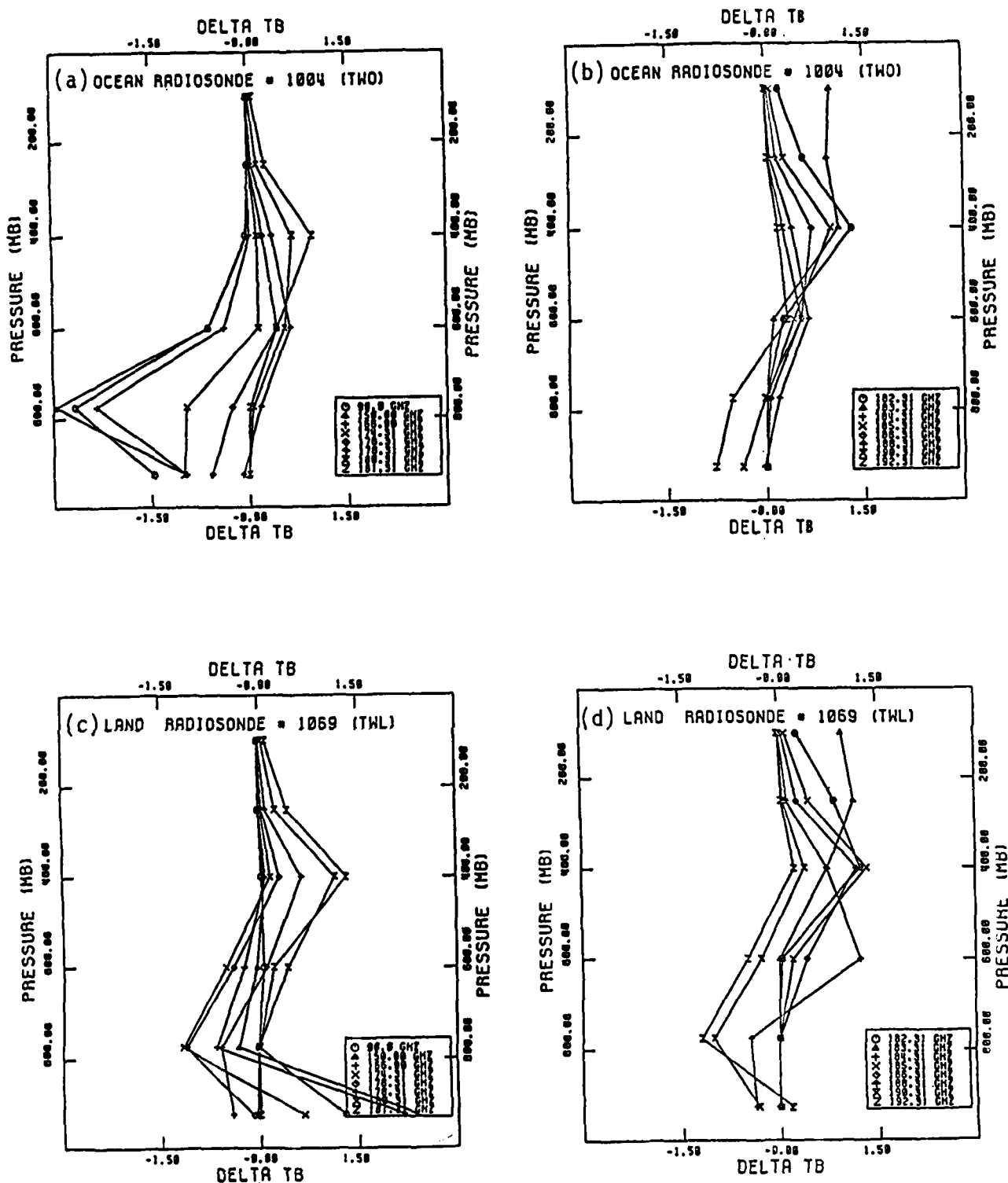


Figure 6. Sensitivity to layer water vapor changes of +20% over the ocean (a), (b) and over land (c), (d) for two selected tropical profiles.

(i.e. $\Delta T_B = T_B(\text{clr}) - T_B(\text{cld})$). The effect of cloud on the weighting functions for one oceanic profile was shown in Figure 5. In the vicinity of the 183 GHz water vapor feature (Figure 7a), channels at ± 5 , ± 7 , and ± 9 GHz from the line center are up to 6 K warmer when viewing the cloud. (One land radiosonde even shows a small cloud effect at 183 ± 3 GHz.) At the window frequencies of 90, 150, and 166 GHz (Figure 7b), the cloud signal is even larger, especially over the ocean where the cloud (like water vapor, see Figure 6a) appears in emission against the radiometrically colder surface. The cloud effect has been verified experimentally with the AMMS aircraft MMW instrument over land during the Cooperative Convective Precipitation Experiment (CCOPE). In that case (see Wang et al., 1983), measured brightness temperatures at 92, 183 ± 2 , 5, 9 were observed to decrease with cloud cover. One land radiosonde in our simulation (#1075) in particular exhibits similar behavior (i.e. mostly positive brightness temperature differences). These sensitivities can be compared and contrasted to those evaluated for water vapor variations at the appropriate levels (about 700 mb) and illustrated in Figure 6. The magnitude of the response to cloud is at least as great as that to water vapor at 90, 150, 166, and 183 ± 5 , 7, 9 suggesting the alternative application of these channels as cloud sensors when appropriate.

Finally, how does the presence of cloud affect the sensitivity of the millimeter wave channels to moisture variations? To investigate the interdependency of cloud and water vapor variations, a simulation experiment was conducted which evaluated the change in brightness temperature due to a 20% increase in the 500-700 mb layer integrated water vapor abundance both in clear situations and in the presence of an underlying layer of stratocumulus clouds extending from 0.5 to 2.0 km. The cloud liquid water content in this case is 0.15 gm^{-3} (Falcone et al., 1979). Occurrence of this cloud type is not uncommon over many oceanic regions (Hahn et al., 1982). Qualitatively, one of the potential advantages of proposed MMW moisture sounders over their infrared counterparts is enhanced sensitivity to low level moisture variations over the ocean (due to the less than unity ($\epsilon \sim 0.7$) MMW emissivity of the calm ocean surface). Over land, this advantage is lost since emissivities are near unity except perhaps over dry snow (A. Chang, personal communication). The results for two land and two ocean radiosondes are presented as a function of channel frequency in Figures 8a and 8b, respectively. The decrease of the

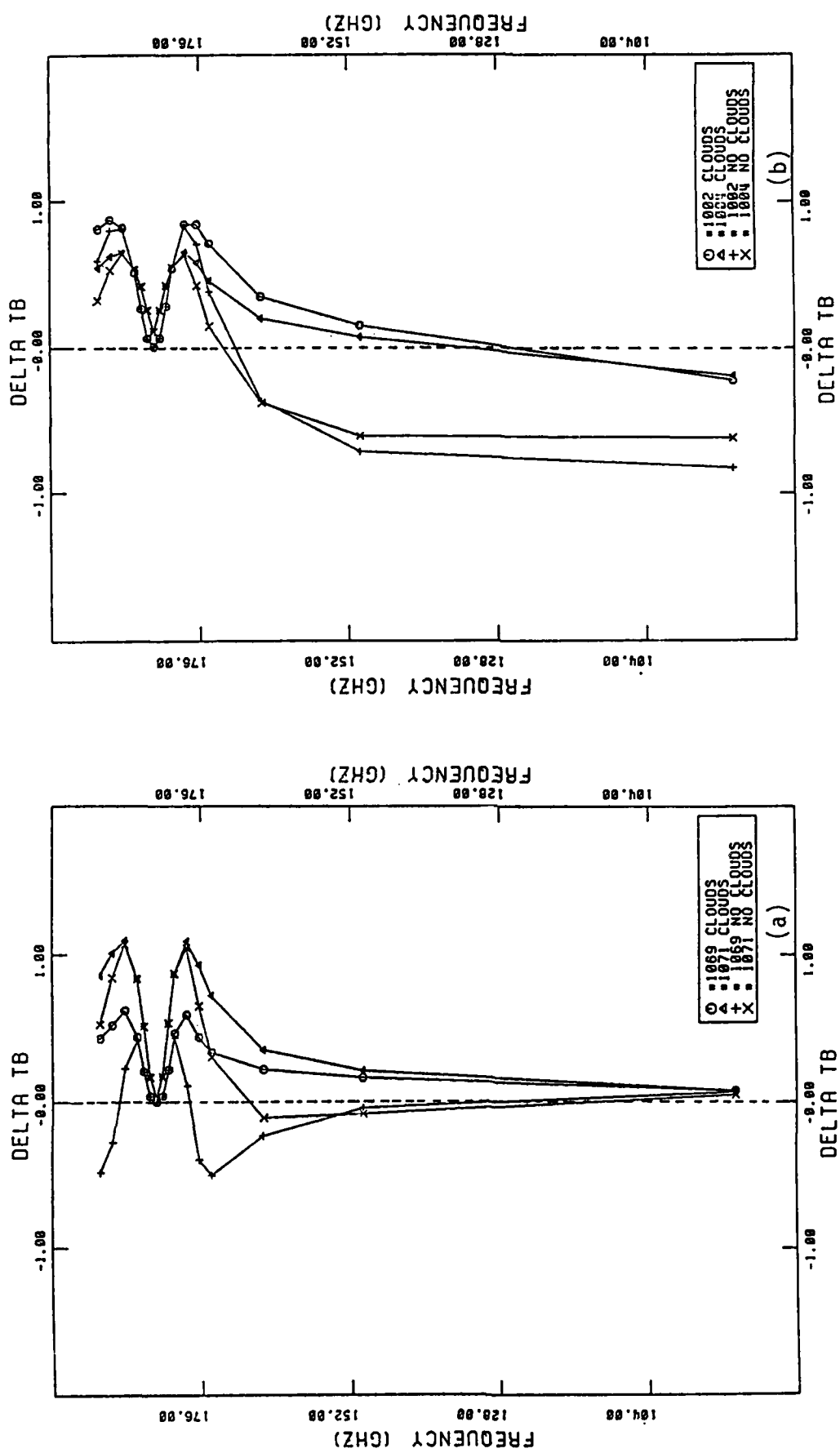


Figure 8. Sensitivity to a +20% change in layer water vapor abundance (500-700 mb) with and without a low level (0.5-2.0 km) cloud over: (a) land radiosondes 1069, 1071) and (b) ocean (radiosondes 1002, 1004).

window channel sensitivities to the water vapor change over the ocean in the presence of the underlying cloud is quite dramatic and underscores the necessity to explicitly treat cloud and water vapor in a unified retrieval approach. With cloud, the frequency dependent brightness temperature sensitivity to water vapor variation over the ocean (Figure 8b), looks very much like that over land (Figure 8a), i.e. the advantage to employing MMW sensors alluded to above is degraded. Notably, over both land and ocean, there is an enhanced sensitivity to water vapor variation in the wings of the water vapor feature at 183 GHz. This behavior may be exploited with a proper cloud treatment.

A number of conclusions can be drawn based on the results of the sensitivity tests alone:

- As perhaps expected, simulated brightness temperatures, particularly for the window frequencies, are very sensitive to precipitation within the field of view (e.g. Figures 3 and 4).
- Changes in layer water vapor abundances of 20% result in channel brightness temperature changes from -3.0 to 2.0 K, depending on frequency, pressure level of the change, and whether the background is land or ocean. In general, a layer water vapor increase results in a brightness temperature decrease for frequencies in the vicinity of the resonance, regardless of background. The exception is the layer nearest the surface which shows little sensitivity to water vapor changes. For window frequencies, water vapor increases generally result in brightness temperature increases over the ocean and decreases over land.
- Significantly, brightness temperatures are quite sensitive to the presence of cloud (Figure 7). For a typical cloud, brightness temperature changes are at least as great as those for a typical water vapor change.
- When cloud appears near the surface over the ocean, sensitivity to variations of water vapor immediately above the cloud are decreased (Figure 8).

As a consequence of this last point, one loses the advantage of decreased surface emissivity over the ocean (i.e. providing enhanced contrast for atmospheric emission near the surface) and the retrieval of water vapor variation in layers near the surface becomes analogous to that over land, i.e. it can no longer be sensed in emission against a "cold" surface.

4.2 Retrieval Studies

Retrieval studies were accomplished by implementing a statistical inversion technique based on the empirical orthogonal functions (EOF) of covariance matrices approach (Gaut et al., 1972, 1973; Smith and Woolf, 1976; Rodgers, 1976). This method is analogous to that used operationally for obtaining microwave temperature profiles from the SSM/T (Rigone and Stogryn, 1977; Grody et al., 1984) and proposed as the primary basis of an approach to millimeter moisture retrieval by Rosenkranz et al. (1982). As applied in our retrievals, layer water vapor abundances obtained from a dependent sample set of radiosondes were regressed directly against brightness temperatures. Retrievals were obtained by using these regression statistics and simulated sensor brightness temperatures to retrieve analogous layer abundances.

More precisely, the technique consists of calculating the eigenvectors of the covariance matrices or empirical orthogonal functions. It uses the eigenvectors of the covariance matrix of the data set (here brightness temperatures) with itself and of the parameter set (here layer integrated water vapor) with itself. An individual retrieval of layer integrated water vapor in r layers from n channel brightness temperatures is obtained from:

$$\hat{u} = C \hat{t} \quad (8)$$

with

$$C = (U T^t)(\hat{T} \Lambda^* \hat{T}^t)^{-1} \hat{T}^* \quad (9)$$

where

\hat{u} is a vector giving an estimate of the profile of integrated water vapor in r layers

\hat{t} is a vector whose components are n brightness temperatures

U_{rs} water vapor at r levels for s atmospheric samples

T_{ns} brightness temperatures for n channels for s samples

\hat{T}^* selected eigenvectors of $T T^t$

Λ^* diagonal matrix whose elements are corresponding eigenvalues

The eigenvectors having relatively small eigenvalue (compared with the largest eigenvalue) are discarded since they only represent noise. In the algorithm

employed only eigenvectors of the covariance matrix of the data set with itself have the possibility to be discarded. As it turns out, the eigenvalues of the covariance matrix of the parameter set with itself are not small enough so that all of them need to be retained. In this method, if none of the eigenvectors are discarded, the problem reduces to that of solving the least squares fit problem, i.e.

$$C = UT^t(TT^t)^{-1} \quad (10)$$

The advantage of the method is that by truncating the sequence of eigenvalues, one reduces the condition number of the matrix, and therefore also the sensitivity to noise. The errors in the data set are introduced randomly using a Gaussian random generator. Each frequency channel can have a different magnitude of error. One can choose the mean and the standard deviation of the error distribution. The mean is always set equal to zero and the standard deviation is what determines the accuracy of a particular frequency channel. In our analysis, no error has been added to the layer integrated water vapor values (i.e. the parameter set).

For our sample of soundings, linearizing the problem by regressing integrated water vapor abundances against brightness temperatures as suggested by Rosenkranz et al. (1982) and others (P. D. Watts, British Met. Office, personal communication) did not improve retrieval accuracy. The channel frequencies given in Table 2 were used to define each sounder "instrument" and instrumental noise was added to each simulated brightness temperature. Three instrumental noise levels were employed corresponding to an ideal, noiseless sensor (noise 0), optimal design noise levels (noise 1), and worst case noise levels (noise 2). Design noise levels were obtained from available technical documentation (cf. Dawkins et al., 1984) and via personal communication (Falcone, AFGL; D. Matheson, RAL).

A quantitative measure of retrieval accuracy was obtained by comparing inferred layer water vapor abundances to those in the actual profiles (the error) and evaluating the fractional root mean square (RMS) error over the ensemble of retrievals. The RMS error for each layer k evaluated over the set of $N = 100$ independent soundings was defined as:

$$RMS(k) = \frac{1}{\bar{u}(k)} \left\{ N^{-1} \sum_{j=1}^N [\hat{u}(k,j) - u(k,j)]^2 \right\}^{1/2} \quad (11)$$

where $\hat{u}(k,j)$ and $u(k,j)$ are, respectively, the retrieved and actual water vapor amounts for the k^{th} and j^{th} sounding and $\bar{u}(k)$ is the layer mean value. For comparison, the same statistic can be evaluated assuming the mean of the ensemble as the "climatological" retrieval for each sounding. This yields the variance of the parent set or the climatology. Figure 9 illustrates the success of each instrument (noise level 1) in retrieving layer water vapor abundance in clear skies over the ocean and land, respectively. The surface emissivity was assumed known in each case (0.7 and 1.0 for ocean and land, respectively). Notably, performance is much better over the ocean, especially for layers near the surface. This is in spite of the larger variance of the oceanic data set. These results may be compared in simulation with those obtained when clouds are present. The regression coefficients for retrieval in this case were evaluated for a separate dependent ensemble of atmospheres to obtain "cloudy" statistics. Clouds were not analyzed based on the atmospheric profile data, rather they were "imposed" randomly from a set of six climatologically representative cloud types. The characteristics of these clouds are described in Table 3.

Table 3
Cloud type characteristics

Type	Liquid Water Content (g l^{-3})	Vertical Extent (km)
1. No cloud	NA	NA
2. Stratus	0.15	0.5-2.0
3. Cumulus	1.00	1.0-3.5
4. Altostratus	0.40	2.5-3.0
5. Stratocumulus	0.55	0.5-1.0
6. Nimbostratus	0.61	0.5-1.0

Since the atmospheric profiles of other variables are given at constant pressure rather than at constant height levels (as the cloud models are given), cloud vertical extent had to be interpolated to the appropriate pressure levels. Therefore, the clouds extend somewhat higher and lower than the

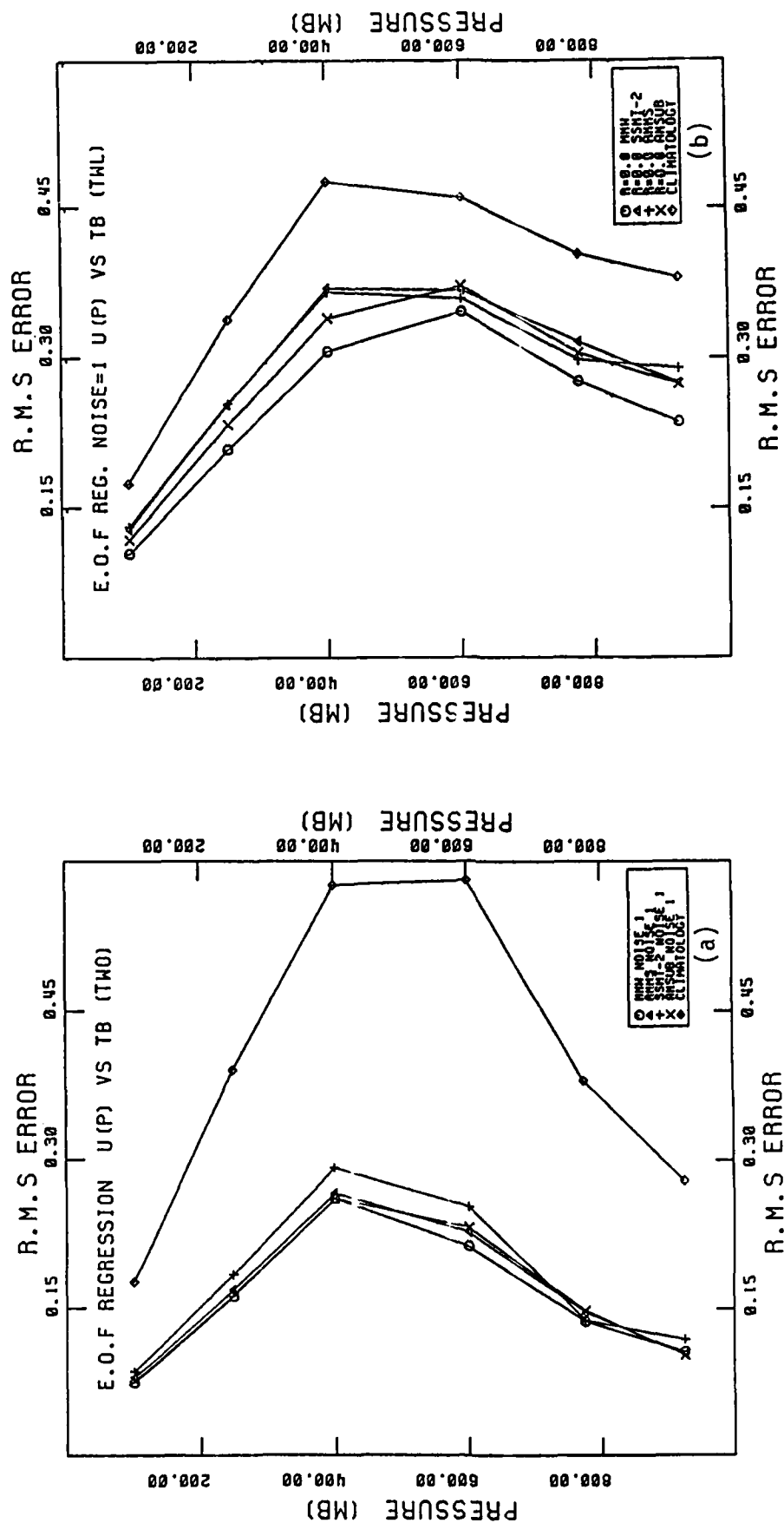


Figure 9. EOF retrieval results for Table 2 instruments and noise 1 over: (a) ocean and (b) land.

maximum and minimum heights given for vertical extent in Table 3. This overlap generally is limited to plus or minus 0.5 km. Additionally, it should be pointed out that relative humidity has not been adjusted within cloud layers. For the tropical atmospheres investigated, requiring saturation within cloud layers had little effect on moisture retrieval results.

Results for cloudy cases are compared to the corresponding clear cases in Figures 10a,b for ocean and land, respectively. The degradation in retrieval performance due to cloud over both land and ocean is quite dramatic. Additionally, Figure 10a demonstrates the effect of uncertainty in the surface emissivity over the ocean on retrieval accuracy. For comparison one set of results used a fixed surface reflectance of 0.3, while another is based on a mean reflectance of 0.3 with an uncertainty of 0.02. The surface reflectance uncertainty (equivalent to an uncertainty in emissivity) does degrade retrieval accuracy somewhat. Further, we can examine the effect of cloud and rain on individual soundings. The results presented in Figures 3 and 4 suggest that brightness temperatures for simulations at frequencies at and above 90 GHz should be drastically altered by the presence of rain of relatively low rainfall rate. Over the ocean, the rain will increase brightness temperatures, while the opposite will be true over land. If neglected, this brightness temperature sensitivity to rain will adversely affect moisture retrievals. Figure 11 illustrates the effect of cloud and rain (a 2 mm/hr drizzle) on the retrieval of moisture for four individual soundings, two each over ocean and land. Retrievals for clear cases (no clouds) were obtained using cloud free a priori statistics while those with clouds and rain were done using cloudy statistics. This means that for clear cases, a dependent set of clear atmospheres was chosen to develop covariance relationship between channel brightness temperatures and layer water vapor amounts. Retrievals were then performed on an independent clear set. For cloudy cases, a similar procedure was undertaken with both sets cloudy. The original soundings are plotted for comparison.

The clear retrievals are rather good especially over the ocean. Those over land provided a less accurate vertical distribution overall, but did well for the integrated amount (since the value near the surface is good in these cases). Cloud and especially rain decrease both the accuracy of the integrated column amount (probably since especially in the case of rain, the sur-

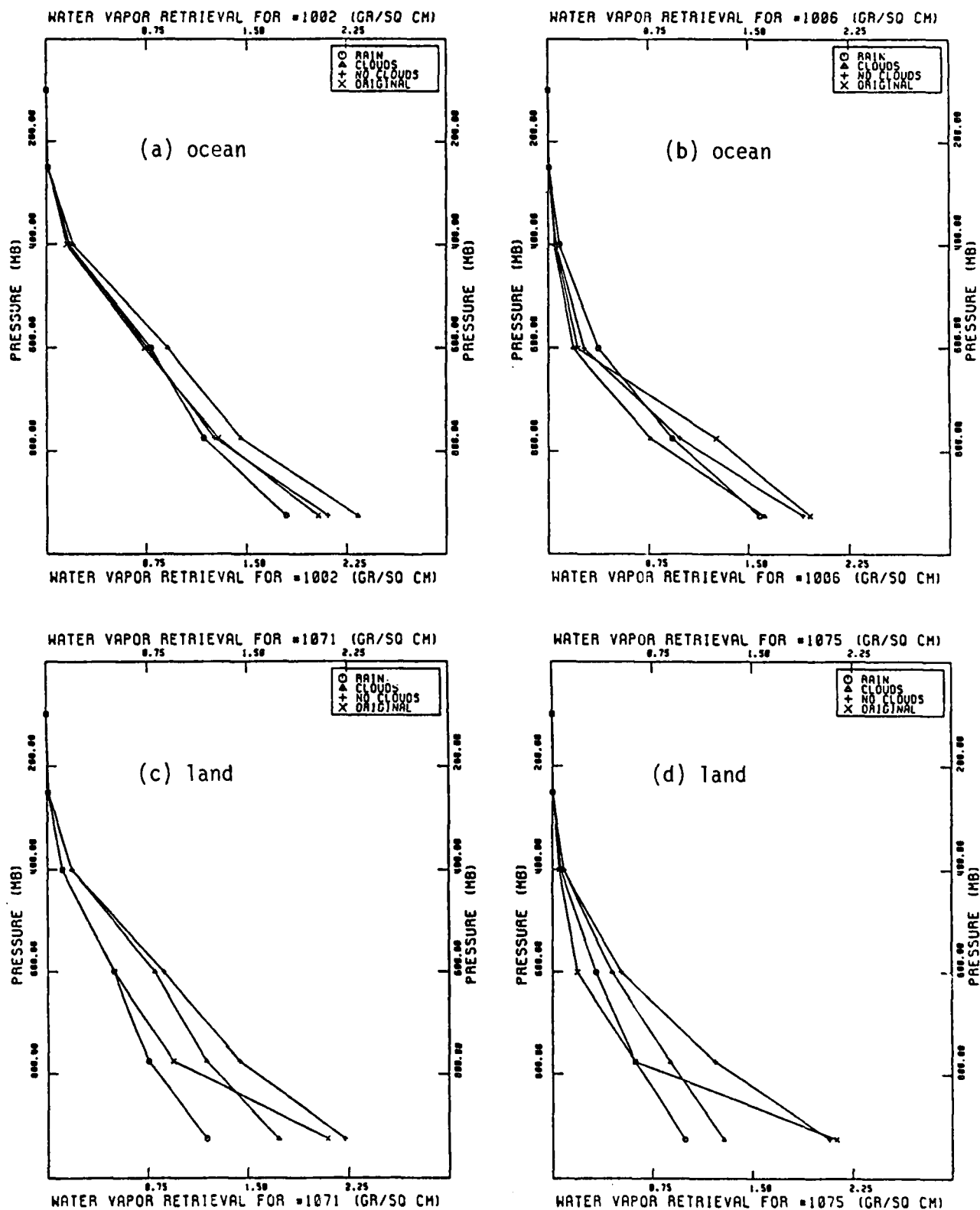


Figure 11. Individual water profile retrieval results for two oceanic (a and b) and two land (c and d) radiosondes showing effect of cloud and rain.

face layer is not "seen") and alter the shape of the retrieved profile. For the two land cases illustrated, the cloudy retrievals actually do better than the clear retrievals in the free atmosphere above 800 mb. The apparent influence of clouds should not be surprising given the results illustrated by the Phase I sensitivity analyses. However, these simulated millimeter wave moisture retrieval test results contrast significantly with those obtained for microwave temperature retrievals where cloud appears to have little effect (Staelin et al., 1975; Liou et al., 1981). Two significant conclusions are drawn based on these limited retrieval assessments:

- cloud will most likely degrade MMW moisture sounder performance;
- since precipitation is optically thicker than cloud, it will generally preclude seeing below affected layers.

5. Summary and Conclusions

This report has described the results of the initial phase of a research and development effort to provide AFGL with instrument response simulation models applicable to the design specification of a 183 GHz microwave moisture sounder. A fundamental technical objective of the study was the development of models capable of treating a realistic range of meteorological variables potentially encountered in the atmosphere, including realistic cloudy and precipitating situations.

The approach employed to accomplish this goal was based on modification and adaptation of the AFGL RADTRAN code for evaluation of gaseous absorption and cloud attenuation and utilization of a multiple scattering (MS) algorithm to treat the effects of precipitation. The specific MS code employed is based on the discrete ordinate method (DOM) described by Liou et al. (1980a). A variety of modifications and enhancements were required to implement the DOM code on the AFGL Cyber for this application including development of a parameterization to provide precipitation scattering optical properties as a function of rainfall rate and phase (i.e. liquid or ice). In addition, interface routines were generated to enable the data base of atmospheric profiles of temperature and moisture used in sensitivity and retrieval studies to be accessed by the simulation algorithm.

The microwave moisture sounder simulation model was exercised to investigate the sensitivity of channel weighting functions and brightness tempera-

tures to the presence of clouds and to variations in layer water vapor abundance in clear cases and against an underlying layer of stratocumulus cloud. Simulations over both oceanic and land background were accomplished employing appropriate surface emissivity values. In performing these sensitivity studies (and the retrieval exercises), a set of frequencies and characteristic instrumental noise levels representative of proposed microwave moisture sounders was selected (see Table 2). Results of the sensitivity studies summarized in Section 4.1 indicate that brightness temperatures for the water vapor sounder channels are quite sensitive to the presence of both cloud and precipitation. The magnitude of the simulated brightness temperature change with water vapor variation in the lower troposphere is generally less than that calculated for the effect of cloud presence, strongly suggesting that cloud is a first order effect. Furthermore, the simulations suggest that the presence of low underlying cloud modifies the surface dependent sensitivity characteristics of the water vapor channels (cf. Figure 8), degrading the enhanced sensitivity of MMW sensors for retrieving low level moisture over the ocean.

In order to ascertain the impact of these effects on the success of moisture retrievals, a statistical inversion technique was implemented (see Section 4.2). Based on the statistical relationship between tropical water vapor abundance in six atmospheric layers and simulated channel brightness temperature for selected sets of channels defining potential sensors, synthetic data (generated by the simulation model) was inverted to obtain moisture profiles. Retrievals were performed for clear and cloudy cases both over land and ocean. The best results (judged by fractional root mean square error evaluated over an ensemble of 100 tropical atmospheres) were obtained for clear cases over the ocean followed by (in decreasing degree of accuracy): clear cases over land, cloudy cases over the ocean, and finally, cloudy cases over land. Based on the results of these preliminary sensitivity and retrieval studies, cloud will most likely degrade MMW moisture sounder performance. Of the instrumental channel sets selected, the hypothetical MMW ten channel instrument did best followed by the AMSU-B. Based on these retrieval results, there is an apparent advantage to a channel in the vicinity of 90 GHz.

6. Recommendations for Future Research and Development

A number of pertinent areas have been identified in the course of this initial study for more extensive research and development efforts. These include both those specific items related to enhancement of the MMW moisture sounder simulation model capabilities and those encountered in the course of analyzing model application to sensitivity and retrieval studies.

6.1 Simulation Model Enhancement

The millimeter wave simulation model developed during this initial study effort and delivered to AFGL is capable of providing realistic simulations for moisture retrieval assessment. In order to enhance its capabilities to more effectively conduct general simulation studies, further work is recommended in (a) the numerical treatment of multiple scattering, (b) evaluation of precipitation scattering parameters, (c) treatment of polarization, and (d) surface emission modeling. These areas are briefly described in the following paragraphs.

The multiple scattering submodel to treat large cloud droplets and liquid and glaciated precipitation is based on the discrete ordinate method as described by Liou (1973) and Liou et al. (1980a). Liou (1973) originally discussed a variety of numerical stability problems associated both with his application of polynomial root searching methods to find the eigenvalues required for solution above and subsequent evaluation of the corresponding eigenvectors. These same troublesome approaches are employed in the algorithm discussed in Liou et al. (1980a) and used in the current model. During our simulation development studies, we noted that newly available, standardized algebraic eigenproblem solution methods would be ideally suited to improve the accuracy and efficiency of the adopted code. This approach had already been tried to solve similar equations for the scattering of solar radiation (Stamnes and Swanson, 1981; Stamnes and Conklin, 1984) using programs available through the IMSL (1975) library. We have successfully tested the approach as applied to the thermal radiation scattering problem relevant to this study using matrix eigensystem routines from the EISPACK (Smith et al., 1976) program set implemented on AER's Harris H800 computer. Calculations using the root searching method for a 16-stream DOM problem (which had required quad precision on AER's computer) were reproduced within machine accuracy using the EISPACK routines in single precision. We estimate a factor

of ten CPU execution time savings in the eigenvalue/eigenvector segment of the scattering submodel when similar efficiencies are implemented at AFGL and suggest modifying the multiple scattering submodel to incorporate this more efficient approach. An immediate result of this task will be less expensive simulations of millimeter wave scattering by precipitation.

In order to characterize the radiative transfer of millimeter waves in precipitating atmospheres it is necessary to accurately obtain the Mie scattering parameters of the distribution of rain or ice droplets (Huang and Liou, 1983). The DOM multiple scattering code requires that an extinction coefficient, single scattering albedo, and coefficients of the Legendre polynomial expansion of the angular scattering (i.e. phase) function be input for each frequency for which a simulation is desired. These parameters will be functions of temperature, phase (i.e. water/ice), and precipitation size distribution (i.e. rainfall rate). Since it would be extremely inefficient to perform a Mie theory calculation online for a given simulation scenario, we developed a parameterization to provide the required values based on Savage's (1978) calculations for up to eight terms of the phase function. It is recommended that the necessary codes to calculate the exact scattering parameters be implemented with appropriate interface routines to obtain efficient parameterizations analogous to those employed here, however. Updated index of refraction data (i.e. Ray, 1972; Warren, 1983) for arbitrary distributions of liquid or glaciated hydrometeors should be employed. These codes will be based on those of Dave (1972) and Wiscombe (1979) and will provide scattering parameters for any number of Legendre polynomial coefficients desired in the phase function expansion.

The importance of an accurate Mie scattering function in the simulation process cannot be overemphasized, particularly at millimeter wavelengths. Figure 12 illustrates the difference between brightness temperatures evaluated using (a) sixteen terms in the phase function expansion and (b) assuming Rayleigh scattering (effectively three terms) as a function of rain rate at seven frequencies extending into the millimeter wave region. Rayleigh (and even less accurately, isotropic scattering) has been used in the past for this type of simulation (cf. the SSM/I development algorithms). Note that while the effect of scattering anisotropy is small at the lower frequencies it increases with increasing frequency (dramatically with rain rate at 90 GHz) and is as much as 10 K at 150 and 166 GHz. Thus, it is extremely important to incorporate Mie (i.e. anisotropic) scattering effects at MMW wavelengths.

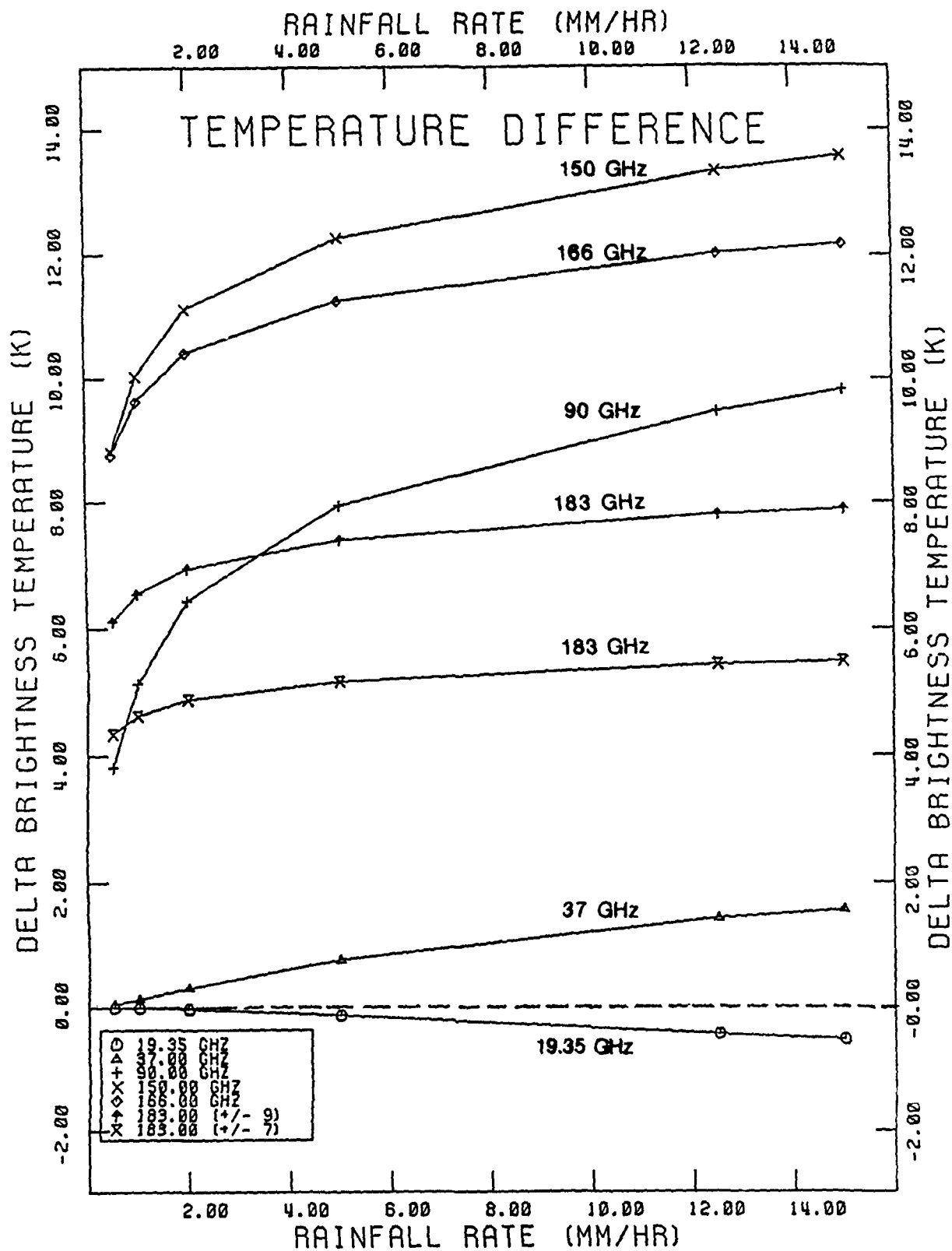


Figure 12. Temperature difference between Mie and Rayleigh scattering as a function of rain rate at seven frequencies.

Many extant microwave multiple scattering simulation models treat only the polarization introduced through the surface reflection of thermal radiation. In these "pseudo" polarized formulations, cross polarization effects within the scattering medium (i.e. scattering of vertical brightness temperatures into the horizontal brightness temperature field and vice versa) are ignored reducing the overall problem to that of solving two scalar radiative transfer equations, i.e. one for each polarization. The MMW simulation model developed here uses this approach. In order to fully model the precipitation physics potentially required (Huang and Liou, 1983; Wu and Weinman, 1984) in the simulation studies in support of retrieval method development, it is recommended to implement a fully vectorized calculation of the radiative transfer process. For this purpose, the code developed by Jin and Kong (1983a,b) may be suggested. Their approach appears most consistent with the currently adopted DOM methodology.

The radiometric properties of the surface are required as boundary conditions in the simulation studies required for retrieval algorithm development. In the initial effort, the values of surface emissivity, both over ocean and "land" have been obtained from a variety of models and studies and varied parametrically. In order to provide a more physical basis for this calculation additional work is required especially over terrain and for snow and ice covered areas. For snow covered areas over land, for example, and oceanic regions containing sea ice, a model based on recent work by Jin and Kong, 1984 and Jin, 1985 is of interest. In this approach the snowpack is modeled as a bounded layer of random spherical discrete scatterers. Both dry and wet snow can be accommodated with the former treated as a mixture of ice particles and air and the latter including the additional constituent of water drops. An analogous approach is applied for various types of sea ice.

6.2 Retrieval Development

The general applicability of the retrieval study results discussed above must be considered within the context of their overall limitations. Retrievals were evaluated using a simple statistical approach based on simulated data evaluated from an atmospheric sample set consisting entirely of tropical atmospheres. Within these constraints, the effect of beam-filling cloud on the retrieval of moisture using millimeter wave sensors is quite evident. Given the above limitations, however, it is certainly appropriate to recommend

extension of the retrieval studies to other global regions and seasonal periods to ascertain their validity. As a minimum, midlatitude and subarctic, latitudes, for example, should be examined in both summer and winter seasons.

One aspect of the retrieval problem which requires more work is realistic modeling of cloudy atmospheres. Even when radiosonde data is identified as "cloudy" there is generally little information, if any, on cloud vertical distribution or liquid water content, both key parameters as indicated above. The oft adopted approach is to impose cloud on clear soundings by some arbitrary criteria (often randomly) and require saturation within cloud layers (cf. Gaut et al., 1975). In this approach, cloud microphysics, cloud top and base, and other relevant properties are chosen from a suitable catalog of models. Our retrieval studies have obtained virtually identical results regardless of whether saturation was assumed within cloud layers or whether the humidity profile was left unmodified. Ideally one would like to use a representative set of upper air sounding with supporting surface observations (including clouds) and concurrent measurements of cloud LWC. As an alternative, we have sought analysis methods which might be applied to surface and upper air data to infer cloud (and precipitation) fields and subsequently assign reasonable cloud liquid water content values. Apparently such techniques have been developed in support of meteorological programs at AFGL (Hardy, 1979) and are described by Feteris et al. (1976) and Bussey (1978). While these techniques were applied manually to site dependent time cross section analyses, they might be appropriately automated in the form of some of the static cloud analysis methods (such as the cloud presence criteria based on dew point depression). Alternately, a suitable data set may be identified which has already been analyzed in this manner.

Finally, if millimeter wave moisture sounders are to be adopted operationally, it would appear to be prudent to recommend investigation of a moisture retrieval methodology which explicitly treats cloud (perhaps in analogy to existing cloud filtering methods applied in the infrared temperature retrieval problem). This may be best accomplished with physical rather than statistical retrievals (Susskind and Reuter, 1984). Furthermore, it is natural to exploit the demonstrated sensitivity of selected simulated MMW channel brightness temperatures to the presence of cloud and precipitation in order to likewise infer their properties as appropriate. Millimeter wavelengths, for example, may be ideally suited to the inference of properties

such as cloud vertical extent not readily available from other spectral regions (Pandey et al., 1983). This generalized geophysical parameter retrieval should be implemented utilizing all available relevant DMSP sensor data (i.e. SSM/T, SSM/I, OLS). This potential approach to the cloud/moisture profile retrieval problem, i.e. as a multispectral/multiparameter system, expresses an emergent philosophy within the state-of-the-art remote sensing community (cf. Susskind et al., 1984a,b; Smith, 1984).

7. References

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